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Weckesser, Johannes Tilman Gabriel; Papangelis, Lampros; Vournas, Costas D. ; Van Cutsem, Thierry

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Local Identification of Voltage Instability from Load Tap Changer Response

Tilman Weckesser^{a,*}, Lampros Papangelis^a, Costas D. Vournas^b,
Thierry Van Cutsem^c

^a*Dept. Electrical Engineering & Computer Science at the University of Liège, Belgium*

^b*National Technical University of Athens, Athens, Greece*

^c*Fund for Scientific Research (FNRS) at the University of Liège, Belgium*

Abstract

This paper presents a local long-term voltage instability monitoring method, which is suitable for on-line applications. The proposed extended-time Local Identification of Voltage Emergency Situations (eLIVES) method is a significantly modified version of the previously presented LIVES method. The new method is not bound to assessing system response over a predefined LTC tapping period. This allows handling LTCs with variable delays, as well as events taking place during the tapping sequence impacting the distribution voltages. For that purpose, eLIVES applies recursive least square fitting to acquired distribution voltage measurements and a new set of rules to detect a voltage emergency situation. The effectiveness of the eLIVES method is presented on the IEEE Nordic test system for voltage stability and security assessment.

Keywords: power system dynamics, voltage stability, on-line stability monitoring

1. Introduction

Since the blackouts that took place in the 80's (e.g. [1]), voltage instability in power systems has been intensively studied [2, 3]. Liberalization of the electricity

*Corresponding author

Email addresses: j.weckesser@ulg.ac.be (Tilman Weckesser),
l.papangelis@ulg.ac.be (Lampros Papangelis), vournas@power.ece.ntua.gr
(Costas D. Vournas), t.vancutsem@ulg.ac.be (Thierry Van Cutsem)

markets has put pressure on power systems and is likely to result in operating
5 conditions closer to stability limits in the near future. For this reason, an early
and reliable identification of developing instabilities or emergency conditions
will become crucial to operate power systems securely. A widespread practice
for voltage stability monitoring is to observe the voltage magnitudes at certain
key transmission buses and issue an alarm, when they drop below pre-defined
10 critical thresholds. For this approach, a major challenge is to define appropriate
thresholds valid for a wide range of disturbances. Recent research efforts have
been focusing on more accurate on-line voltage stability monitoring and early
detection of developing voltage instability. The aim of these methods as well
as the one proposed in this paper is to identify an evolving instability before
15 it is apparent from sole observation of bus voltage magnitudes. A review of
existing voltage instability detection methods has recently been published in
[4]. The developed methods are either attempting to detect voltage instability
on a system-wide level or purely locally. Detection methods utilizing wide-
area measurements are, for example, based on decision trees [5] or suitable
20 voltage stability indices [6, 7, 8]. Some of the system-wide methods require full
system observability obtained from PMUs, which is not yet available. However,
a combination of PMUs with SCADA measurements can already today provide
full system observability.

Local methods require only locally available measurements, which are easily
25 accessible. A group of local methods attempts to determine voltage stability
through detection of the impedance matching condition [9, 10, 11]. Another local
method, called Local Identification of Voltage Emergency Situations (LIVES)
[12, 13], is utilizing measurements, which are readily available in the Load Tap
Changer (LTC) controlling bulk power delivery transformers. In order to early
30 detect voltage instability, LIVES solely monitors the voltage magnitude on the
controlled, distribution side of the transformer. This voltage is not only affected
by the local LTC, but reflects the combined effect of all voltage controllers in the
system, e.g. other LTCs, OverExcitation Limiters (OELs) and shunt capacitor
switching. Figure 1 shows an example of a voltage magnitude at a Medium

35 Voltage (MV) bus, the ratio of the local transformer and the voltage magnitude at the corresponding High Voltage (HV) bus. It can be observed that the

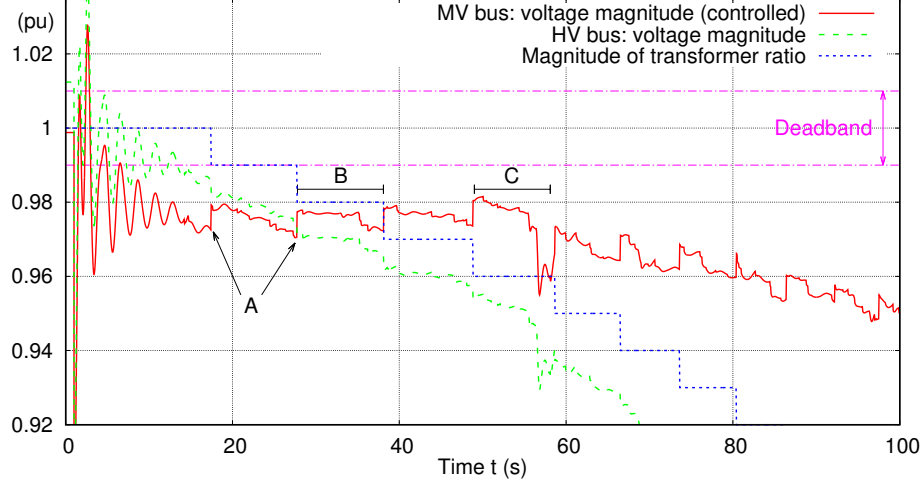


Figure 1: Example of combined effect of local LTC and other voltage controllers in a voltage long-term voltage unstable evolution after a line outage.

voltage magnitude at the HV bus is declining after the initial outage, under the effect of multiple tap changes (including the one shown in Fig. 1). After the initial oscillations of the MV voltage, induced by a fault and its clearance, damped out, it can be observed that each tap change in the shown transformer (identified by the jumps in the dashed blue curve) temporarily increases the corresponding MV bus voltage magnitude (see *A* in Fig. 1). This temporary increase is to some extent canceled by the effect of other tap changers as well as field current limiters. An almost complete cancellation of the benefit of the local tap change can be observed in the time interval marked *B* in Fig. 1, while during the period marked *C*, the other tap-changes and field current limitations clearly prevail. From this time on, an overall negative trend of the distribution voltage magnitude can be observed, which is typical for long-term voltage instability.

The early detection of the above unsuccessful distribution voltage restoration is the topic of this paper. It should also be mentioned that, in near future, the response of active distribution grids will play a role in voltage recovery. However,

in this paper the focus is on the effect of load tap changers.

The LIVES method described in [12] relies on the assumption that LTCs apply a constant tap delay. On the contrary, this paper proposes an approach
55 that encompasses the case when LTCs have variable tap delays, e.g. obeying an inverse time characteristic, where the tap delay decreases with an increasing deviation of the controlled voltage from its set-point (as in the example of Fig. 1).

The development of the proposed extended-time LIVES (eLIVES) method was motivated by the idea of considering the whole distribution voltage recovery
60 after an unforeseen event instead of looking at an incremental behavior over one tapping period.

The paper is structured as follows. In Section 2 the original LIVES method [12] is summarized and reasons for its non-applicability in the case of variable-delay LTCs are presented. In Section 3, the recursive least squares approach,
65 which is used to fit a linear regression model to the voltage evolution at the LTC controlled bus, is explained. Then the rules used for the detection of a voltage emergency situation are introduced. The IEEE Nordic Test System used for the validation of the proposed method as well as the obtained simulation results of the identification of voltage emergency situations are discussed in Section 4.
70 In Section 5 an application of eLIVES to emergency control is presented and Section 6 presents an assessment of the methods robustness, when noise is added to the measurement samples. Finally, some concluding remarks are offered in Section 7.

2. Principle and limitations of the LIVES method

75 The LIVES method [12] relies on the individual monitoring of distribution transformers, equipped with LTCs. Essentially, the method identifies an evolving long-term voltage instability through the fact that the positive effect on the controlled voltage of a local tap change is canceled by tap actions of other transformers and similar events in the system.

80 For that purpose, LIVES observes the controlled voltage over a time interval

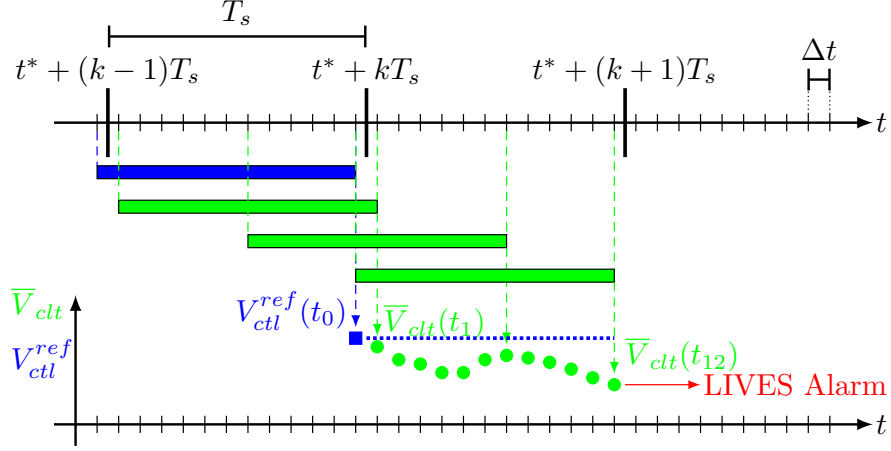


Figure 2: Visualization of the MA calculation in LIVES at an LTC with constant tap delay T_s

including a single tap change of the local transformer. To filter measurement noise and transients, a Moving Average (MA) of the voltage is computed. The MA's sliding window size is chosen equal to the time between two tap changes. Figure 2 is used to explain how MA computation and monitoring work. On
85 the upper time line, the shorter vertical ticks indicate the discrete times, where voltage measurement samples are collected. The sample rate is Δt . The longer vertical ticks depict times at which tap changes occur in the monitored transformer. It is assumed that the LTC applies a constant delay T_s between successive tap changes and that the controlled voltage does not re-enter the deadband
90 during the displayed time period. t^* corresponds to the time of the first tap change; hence, the subsequent tap changes occur at t^* plus a multiple of T_s . The blue and green bars correspond to the time window, used to compute the respective MA. On the lower time line, the shorter vertical ticks again show the discrete times, where samples are collected. On the ordinate, the computed MA
95 of the controlled voltage (\bar{V}_{ctl} , green circles) and a reference value (V_{ctl}^{ref} , blue squares) are shown.

The implementation of LIVES can be summarized as follows [13].

1. Before a tap change, e.g. at the discrete time t_0 , the Moving Average

$\bar{V}_{ctl}(t_0)$ of the controlled voltage V_{ctl} is calculated as follows:

$$\bar{V}_{ctl}(t_j) = \frac{1}{n} \sum_{k=0}^{n-1} V_{ctl}(t_j - k\Delta t) \quad (1)$$

where n is the number of samples involved. In order to ensure that only one tap change is included in the computation of the MA, n is computed to correspond to the constant tap delay T_s of the respective LTC:

$$n = \left\lceil \frac{T_s}{\Delta t} \right\rceil \quad (2)$$

This MA is stored as a reference value.

$$V_{ctl}^{ref}(t_0) = \bar{V}_{ctl}(t_0) \quad (3)$$

2. At every sampling step $t_j = t_0 + j\Delta t$ ($j = 1, \dots, n$) the MA is updated using (1). It is then compared to V_{ctl}^{ref} . If the MA exceeds this reference, (indicating that voltage is recovering) no further check is going to be performed until a new reference is computed. On the other hand, if the MA remains below the reference for a period of at least T_s an alarm is issued.
3. Before the next tap change and if the MA at some point exceeded the reference, a new reference is taken equal to the MA just before the tap and the monitoring is continued as described above.

In the example shown in Fig. 2, the reference V_{ctl}^{ref} is computed at t_0 and the subsequent MA $\bar{V}_{ctl}(t_j)$, which are computed with the samples in the respective window, are compared to it at times t_1, \dots, t_{12} . In the shown case the MAs remain below the reference for the entire period T_s and, hence, LIVES raises an alarm after $\bar{V}_{ctl}(t_{12})$ has been evaluated.

It is apparent that for computing the MA and the reference value, the time until the next tap change needs to be known as well as the tap delay T_s . This information is easily obtainable, if the LTC applies a constant delay. However, if the delay varies (with the voltage deviation) the above MA comparison is no longer valid. Figure 3 shows an example, where the time T_2 between the second and third tap change is shorter than T_1 between the first and second tap change.

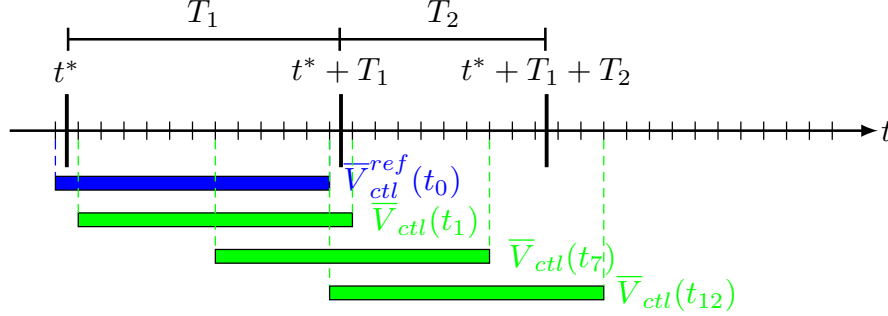


Figure 3: Visualization of the MA calculation in LIVES at an LTC with variable tap delay

If the MA window is chosen equal to T_1 , then during the observation period some MAs, e.g. $\bar{V}_{ctl}(t_{12})$ (see Fig. 3), will be computed based on samples containing two tap changes, which is overoptimistic. Alternatively, when the shorter tap delay is discovered, the MA window could be reduced to T_2 and the latest reference could be updated. However, to this purpose the new reference should be based on the period T_2 . Since $T_1 > T_2$, the samples used for this computation would not include a tap change and, hence, the assumption underlying the LIVES method would be violated again (this time being overly pessimistic).

To summarize, the underlying stability criterion of LIVES requires a synchronization with the LTC and the MA is a numerical filter appropriate only for fixed tap delays. These prerequisites are not fulfilled in the presence of LTCs with variable tap delay and, consequently, the LIVES method cannot be directly applied.

This limitation prompted the development of the eLIVES method described in the next section.

3. Extended-time Local Identification of Voltage Emergency Situations

The eLIVES method is based on the detection of a decreasing trend of the secondary (controlled) voltage and a drop of the primary voltage below a predefined threshold during the post-disturbance evolution. The criterion uses

only local available measurements and information, namely the primary voltage magnitude V_{HV} , the secondary voltage magnitude V_{ctl} , the width of the half-deadband δ , transformer ratio and maximum tap delay T_{max} , which corresponds
140 to the maximum delay when V_{ctl} is just outside of the deadband of the respective LTC.

The method is executed when a significant disturbance in the system is detected and the secondary voltage leaves the deadband, while the LTC is still active, i.e. it has not yet reached its hard tap limits. After the detection of
145 the first tap change, the method begins to record voltage measurements. These measurements are utilized to identify the trend of the voltage evolution using a linear regression model.

3.1. Recursive least square fitting of voltage measurements

In each time step t_i , the estimator determines a linear regression model, which is assumed to show the overall trend of the monitored voltage:

$$V_f(t) = m_i t + b_i \quad (4)$$

In the post-disturbance configuration, secondary voltage samples are gathered to determine a linear (in time) approximation of the voltage evolution. For that purpose, the following equations need to be solved in least squares sense:

$$\mathbf{V}_i = \begin{bmatrix} V_1 \\ V_2 \\ \vdots \\ V_i \end{bmatrix} = \underbrace{\begin{bmatrix} t_1 & 1 \\ t_2 & 1 \\ \vdots & \vdots \\ t_i & 1 \end{bmatrix}}_{\mathbf{A}_i} \underbrace{\begin{bmatrix} m_i \\ b_i \end{bmatrix}}_{\boldsymbol{\theta}_i} \quad (5)$$

where \mathbf{A}_i is the regression matrix and $\boldsymbol{\theta}_i$ is the corresponding parameter vector
150 determined at t_i .

Since the method assesses long-term voltage stability, which may require several minutes of monitoring after a disturbance, using a conventional least squares approach may not be feasible. For that reason, the model is fitted using

a recursive least squares (RLS) approach [14], which has the advantage that, although all recorded measurements are considered, no large history needs to be processed at each time. The model is updated solely by processing the newest measurement. When a new measurement is received, the parameter vector θ_i is updated by the RLS estimator as follows:

$$\theta_i = \theta_{i-1} + R_i^{-1} a_i (V_i - a_i^T \theta_{i-1}) \quad (6)$$

where a_i is the regressor $[t_i \ 1]$ and R_i the covariance matrix at time t_i . The inverse of the covariance matrix can be directly updated according to:

$$R_i^{-1} = R_{i-1}^{-1} - R_{i-1}^{-1} a_i (1 + a_i^T R_{i-1}^{-1} a_i)^{-1} a_i^T R_{i-1}^{-1} \quad (7)$$

Since (7) allows directly updating the inverse of the covariance matrix, the inversion is performed only at the initialization. To compute a first estimate of the parameters, at least two successive measurements of the voltage magnitude are acquired, and the covariance matrix R_i is computed as follows:

$$R_i = A_i^T A_i \quad (8)$$

In this paper, all measurements are considered and, hence, no forgetting factor was introduced.

The slope of the estimate m_i is then used in the process of identifying a voltage emergency situation. Figure 4 shows two examples of the recorded volt-

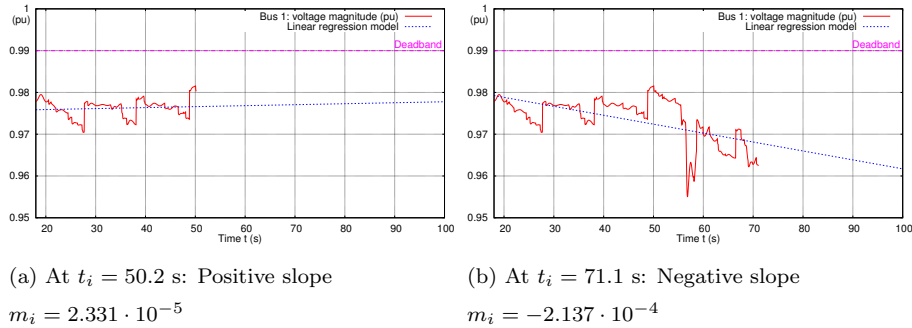


Figure 4: Comparison of the fitted linear regression model at two time instants.

age and the respective fitted linear regression model. Since the aim is to assess the overall trend of the voltage, the RLS approach without forgetting factor is employed, which considers all measurements from the start of the monitoring (here $t = 18.0$ s) and until the current time (in Fig. 4a 50.2 s and in Fig. 4b 71.1 s, respectively). In Fig. 4a a general improvement of the voltage magnitude and a positive slope of the fitted model can be observed, while Fig. 4b shows a declining voltage magnitude and a negative slope. Consequently, the proposed stability index is determined based on the monitored slope of the fitted linear regression model.

3.2. Rules for identification of a voltage emergency situation

In order to efficiently detect an emergency situation, a set of rules has been derived. The algorithm is activated when the controlled voltage leaves the dead-band and voltage measurements are acquired to estimate the overall trend of the voltage. If a negative trend (declining voltage magnitude) is identified, an eLIVES Warning is issued. If additionally a drop of the voltage V_{HV} on the primary side greater than a pre-defined threshold ΔV_{crit} is detected, an eLIVES Alarm is raised. The pseudo-code of the algorithm executed at time t_i is shown next.

```

1: if  $V_{ctl}(t_i) < V_{set} - \delta$  then
2:   if recording = off and tap change occurred then
175 3:     recording := on;  $t_{DB} := 0$ ;  $t_{rec} := t_i$ 
4:   else
5:     if  $t_{DB} > 0.0$  then
6:        $t_{DB} := 0.0$ 
7:     end if
180 8:   end if
9: else
10:  if recording = on then
11:    if  $t_{DB} = 0.0$  then

```

```

12:       $t_{DB} := t_i$ 
185 13:  else
14:      if  $t_i - t_{DB} > T_{off}$  then
15:          recording := off
16:      end if
17:  end if
190 18: end if
19: end if
20: if recording = on then
21:     if NOT ( $N_i = N_{min}$  and  $t_i - t_{tap} > T_{max}$ ) then
22:         Determine RLS fit of  $V_{ctl}(t)$  from  $t = t_{rec}$  to  $t = t_i$ 
195 23:     if  $m_i \geq 0.0$  then
24:          $m_{i-1} := None$ ; eLIVES Warning := False;
25:         eLIVES Alarm := False;
26:     else
27:         if no previous slope  $m_{i-1}$  was stored: then
200 28:              $m_{i-1} := m_i$ 
29:         else
30:             if  $t_i - t_{rec} > T_{max}$  then
31:                 if  $m_{i-1} - m_i > 0.0$  then
32:                     eLIVES Warning := True
205 33:                 end if
34:                  $m_{i-1} := m_i$ 
35:             end if
36:         end if
37:     end if
210 38:     if  $V_{HV}(t_{rec}) - V_{HV}(t_i) > \Delta V_{crit}$ 
        and eLIVES Warning then
39:         eLIVES Alarm := True
40:     end if
41: end if

```

```

215 42:   if  $V_{HV}(t_i) < V_{HVAlarm}$  then
43:       HV Alarm := True
44:   end if
45: end if

```

220 The algorithm is stopped, when the voltage remains in the deadband for longer than T_{off} . In the following the algorithm will be explained in detail. In order to refer to parts of the algorithm, the text will refer to particular line numbers in the algorithm (*AL*).

The beginning of the algorithm (*AL1 – 19*) shows the reasoning to determine if the monitoring with eLIVES should be started, continued or stopped. If the voltage V_{ctl} leaves the deadband (*AL1*) and a tap change was detected (*AL2*), the monitoring with eLIVES is activated at $t_{rec} = t_i$. Then the method starts to record samples of the secondary voltage magnitude. Additionally, t_{DB} , which indicates the time when V_{ctl} re-enters the deadband, is reset (see *AL3*). The requirement of the detection of a tap change ensures that the monitoring is only activated, if the LTC is not yet at its limit. After activation, when the transformer ratio N_i of the LTC reached its hard tap limit N_{min} , the monitoring with eLIVES is stopped after a delay equal to the respective maximum tap change delay T_{max} (*AL21*). eLIVES aims at locally identifying a voltage emergency situation, which is driven by the effect of the local LTC combined with all voltage controllers in the system. When the LTC exhausts its tap range voltage control is lost at the particular bus and it is no longer contributing to the developing voltage instability.

240 The recorded voltage magnitude samples are used to fit the linear regression model as described in section 3.1. It was found that to correctly identify the overall trend of the voltage trajectory, it is beneficial to continue sampling the voltage magnitude even when it temporarily enters the deadband. Hence, the fitting of the secondary voltage is stopped only if the voltage remains inside the deadband longer than a time T_{off} indicating that the system long-term dynamics have reached an equilibrium (see *AL9 – 19*).

245 3.2.1. *eLIVES Warning*

When a sufficient number of samples is collected the linear regression model is fitted (see AL22). The slope m_i of the fitted line is utilized in the evaluation process (see AL23). A negative slope indicates that the voltage magnitude is declining and may indicate a deterioration of the system conditions, while a
 250 positive slope suggests an overall recovery of the voltage and improvement of the system conditions. Consequently, if the determined slope is positive, the controller is reset and issued warnings/alarms are cleared (see AL23 – 25). In the case that the determined slope is negative, it is compared to the negative slope m_{i-1} , which was determined with the previous sample. A warning
 255 (eLIVES Warning) is issued, if the current slope m_i is more negative then the slope m_{i-1} (see AL31 – 33).

For improving the performance of the method, the evaluation of m_i and m_{i-1} is delayed by T_{max} (see AL30). The delay was chosen to give the LTC time to restore the voltage and to allow revelation of the overall voltage trend.

260 3.2.2. *eLIVES Alarm*

After an eLIVES Warning has been raised, the voltage on the primary side V_{HV} of the transformer is used to determine, if an eLIVES Alarm should be issued. Subsequently, this alarm may be used to trigger corrective actions such as undervoltage load shedding, reverse tapping, etc. An eLIVES Alarm is trig-
 265 gered, if an eLIVES Warning was issued and the voltage magnitude on the primary side dropped by more than ΔV_{crit} (e.g. 0.05 pu) with respect to its value at $V_{HV}(t_{rec})$ (see AL38 – 40). This acts as a safeguard requiring the observation of a certain voltage drop on the primary side before corrective actions are executed and it serves as an intentional, but indirect, delay while the voltage
 270 drop is not yet significant enough to take corrective actions.

3.2.3. *HV Alarm*

This alarm is triggered, when the voltage magnitude of the primary side falls below a critical value defined by the system operator, e.g. $V_{HVAlarm} = 0.9$ pu.

Contrary to eLIVES Alarm, it is also triggered when the LTC succeeds in restoring the voltage on the secondary side, but the successive tap changes led to unacceptable low voltage on the primary side (see *AL42 – 44*).

3.2.4. Parameters of eLIVES

eLIVES requires only few parameters, namely T_{off} , ΔV_{crit} and $V_{HVAlarm}$. If eLIVES was activated, but the controlled voltage has been restored and has re-entered the deadband, T_{off} corresponds to the time that eLIVES remains active. This time constant should be chosen long, e.g. 250.0 s, to account for delays of other voltage controllers in the system. ΔV_{crit} corresponds to the voltage drop on the HV side, which should be observed before emergency control actions are triggered. The HV alarm serves as a back-up alarm and, hence, the threshold $V_{HVAlarm}$ can be chosen low, e.g. 0.9 pu. The ΔV_{crit} and $V_{HVAlarm}$ parameters are used quite often by Transmission System operators in static security assessment of their grids. Although they vary from one system to another, the values used in this paper are quite representative.

Other needed parameters are obtained from the settings of the respective LTC, such as the maximum tap delay T_{max} , the width of the half-deadband δ and the lower hard tap limit N_{min} .

4. Simulation results - Identification of emergency situations

4.1. IEEE Nordic Test System

In order to demonstrate the dependability and security of the proposed eLIVES method, the Nordic test system proposed by the IEEE Task Force on Test Systems for Voltage Stability and Security Assessment is utilized. The detailed data of the test system as well as the operating points can be found in [15]. A one-line diagram can be seen in Fig. 5.

As described in [15] all MV loads are served through distribution transformers equipped with LTC. The width of the half-deadband δ is equal to 0.01 pu. Contrary to [15] the LTCs do not have constant tapping delays, but variable

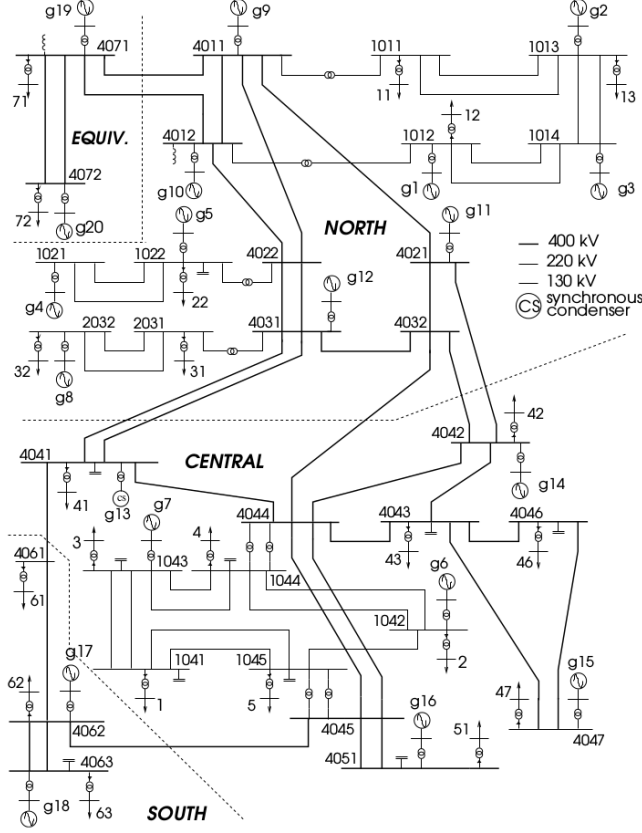


Figure 5: One line diagram of the IEEE Nordic test system [15]

delays with an inverse time characteristic. Hence, the tap delay is dependent on the observed voltage deviation; a larger deviation results in a shorter delay and vice versa. An important parameter for an LTC with inverse time characteristic is the maximum tap delay T_{max} . In the simulations, it was chosen in the range of 25 – 40 s.

For the eLIVES controllers only few parameters need to be selected: $T_{off} = 250$ s, $\Delta V_{crit} = 0.05$ pu and $V_{HV Alarm} = 0.9$ pu. Moreover, it is assumed that the individual controller samples local voltage measurements every 0.5 s.

310 4.2. Scenarios and operating points

The proposed method is tested on three scenarios, which are described in detail in [15]. In all scenarios the same disturbance was considered, which is a solid three-phase fault occurring at $t = 1.0$ s close to bus 4032 and which is cleared after 100 ms through tripping of line 4032 – 4044.

- 315 • **Scenario 1 - Operating point A:** The fault causes long-term voltage instability and a system collapse.
- **Scenario 2 - Operating point B plus 350 MW:** Operating Point (OP) B is obtained from OP A, but modified to be secure with respect to the aforementioned disturbance. The adjustments are detailed in [15]. In
320 OP B plus 350 MW, the loading of the Central region has been uniformly increased by a total of 350 MW. As a result, the case is marginally stable, which means that the system conditions are severely deteriorated, but the voltage magnitudes at all buses eventually settle at acceptable levels.
- **Scenario 3 - Operating point B plus 375 MW:** The loading in the
325 Central region was uniformly increased by 375 MW. The case is marginally unstable, and the voltage magnitudes at some buses settle at unacceptable low values.

4.3. Scenario 1 - Operating point A

Figure 6 shows a selection of HV bus voltages. It can be observed that a
330 collapse in voltage occurs in the Central area, while the voltages in the Northern and Southern areas are little affected. After the contingency, oscillations can be seen, which damp out after approximately 20 s when the system reaches a short-term equilibrium. Subsequently, LTCs are acting to restore the voltages in the system and OELs are activated to protect the field windings of the respective
335 generators. This eventually leads to a system collapse after less than 140 s.

Table 1 shows the assessment results of eLIVES. The table lists the buses at which a warning or alarm was raised. As described in Section 3.2, an eLIVES

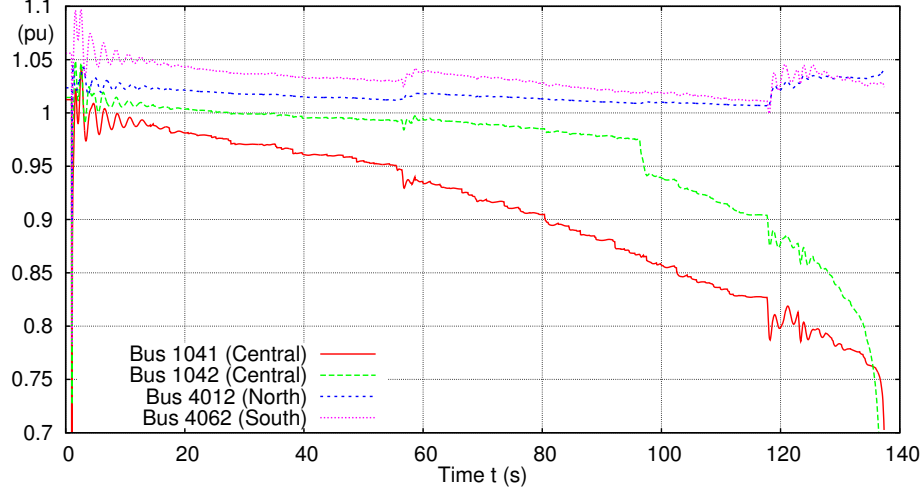


Figure 6: Scenario 1 - Selection of transmission voltages in Central, North and South region.

Warning is raised, when a negative trend of the controlled voltage V_{ctl} is observed. Subsequently, an eLIVES Alarm is raised, if additionally the respective voltage on the primary side V_{HV} dropped by more than ΔV_{crit} . The HV Alarm serves as a backup, since it is solely triggered, if V_{HV} drops below the pre-set value $V_{HV Alarm}$.

The table shows that for a number of buses warnings were issued. These buses are either in the Central area (1 – 5, 41 – 43, 46, 47 and 51) or are adjacent to the Central area (South: 62; North: 22 & 31). However, alarms have been issued almost exclusively at buses in the Central area. Moreover, it should be noted that the eLIVES Alarms were raised 15.8 – 38.5 s earlier than the HV Alarm at all buses. This shows a clear advantage of the eLIVES Alarm, since an earlier alert leaves more time to initiate counter actions.

Figure 7 displays the voltage evolutions at the MV bus 1 (red solid line) and the HV bus 1041 (green dashed line) as well as the ratio of transformer 1 – 1041 (blue dotted line) connecting these two buses. It can be observed that after a time delay the corresponding LTC attempts to restore the voltage by decreasing the transformer ratio. However, the LTC does not succeed in

Table 1: Scenario 1 & 3- Issued warnings and alarms.

Bus	Scenario 1			Scenario 3		
	eLIVES Warning	eLIVES Alarm	HV Alarm	eLIVES Warning	eLIVES Alarm	HV Alarm
1	58.2	58.2	80.8	— ²	— ²	402.1
2	89.0	97.8	118.2	719.5	755.8	835.5
3	58.8	61.5	92.3	— ²	— ²	683.7
4	66.5	67.0	84.6	— ²	— ²	716.2
5	75.8	75.8	95.6	708.5	708.5	777.8
22	98.9	—	—	400.6	—	—
31	102.8	102.8	—	—	—	—
41	80.8 ¹	80.8	118.2	—	—	—
42	58.8	60.4	98.9	— ²	— ²	887.2
43	67.6	74.2	112.1	796.5	796.5	854.2
46	69.2	80.8	118.2	804.2	804.2	853.7
47	86.3	102.8	118.7	—	—	—
51	97.8	105.5	130.6	—	—	—
62	92.3	—	—	—	—	—

¹ : Early warning at 56.6 s

² : Assessment with eLIVES was stopped since the LTC hit its limit.

355 restoring the voltage and a declining trend of the voltage magnitude can be
observed. Moreover, Fig. 7 shows that due to the inverse time characteristic
of the LTC the tapping delay is decreasing with increasing depression of the
voltage magnitude. eLIVES early identifies the negative trend of the voltage
evolution and issues a warning at $t_i = 58.2$ s. At this time, the voltage on the
360 HV side already fell by 0.05 pu with respect to its value at t_{rec} and, hence, also
the alarm is raised. Eventually, the HV voltage falls below 0.9 pu and the HV
Alarm is set at $t_i = 80.8$ s.

Figure 8 shows the voltage evolution at the MV bus 31 (red solid line) and

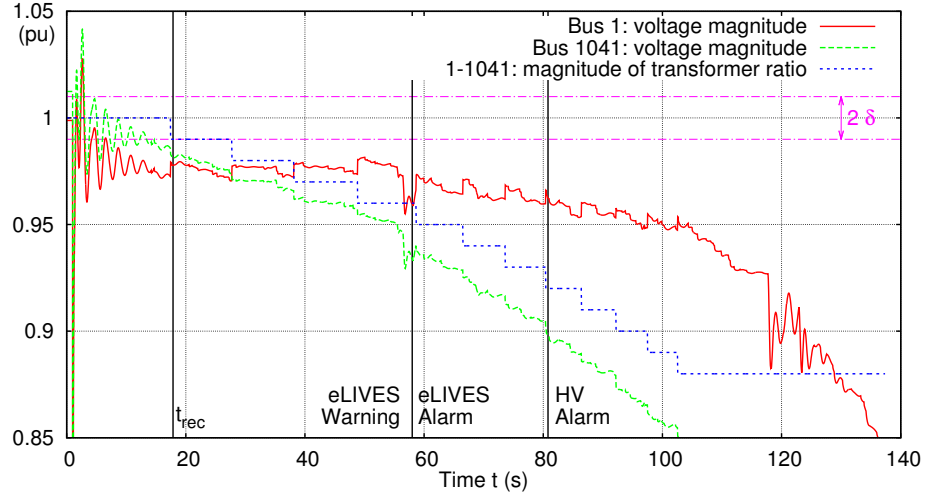


Figure 7: Scenario 1 - Bus voltage magnitude at HV bus 1041 and MV bus 1. Transformer ratio of transformer 1 – 1041.

the HV bus 2031 (green dashed line), together with the transformer ratio (blue dotted line). Bus 31 is the only bus in Table 1 where an eLIVES Alarm is raised but no HV Alarm. The graph shows that the LTC does not succeed

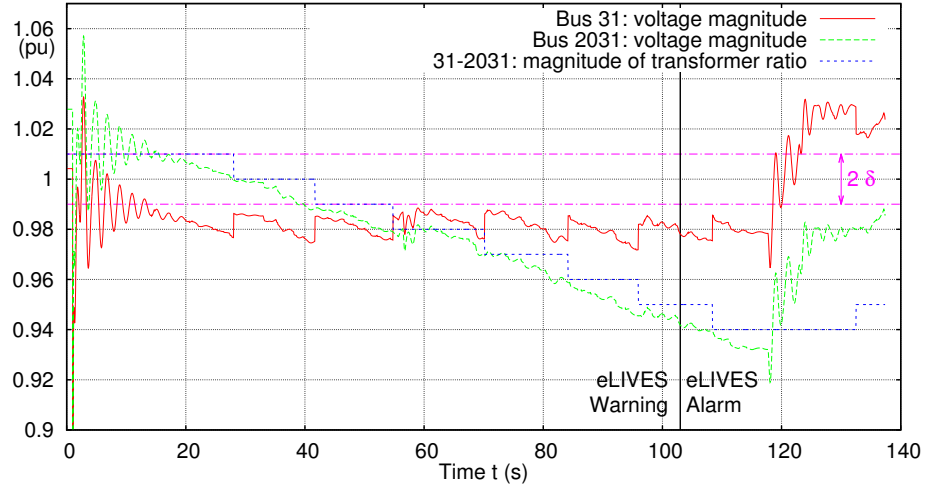


Figure 8: Scenario 1 - Bus voltage magnitude at HV bus 2031 and MV bus 31. Transformer ratio of transformer 31 – 2031.

in restoring the controlled voltage until $t_i \approx 118$ s. The voltage at the bus only recovers, when the voltage in the Central area collapses. Moreover, due to the repeated tap changes the HV voltage gets severely depressed. The eLIVES method detects a negative voltage trend and a serious depression of the HV voltage magnitude at $t = 102.8$ s, which results in issuing of an eLIVES Warning and Alarm. Since the LTC 31 – 2031 does not participate in the instability and the voltage at the controlled bus is eventually restored, this case is considered to be a false alarm. However, this false alarm is raised only after nine real alarms and any countermeasure taken in the mean time at any of these nine buses could avoid it.

4.4. Scenario 2 - Operating point B plus 350 MW

In this marginally stable case, the proposed method does not raise any warnings or alarms. This is due to the fact that all voltages in the system can be restored to an acceptable level. Figure 9 shows the successful restoration of the

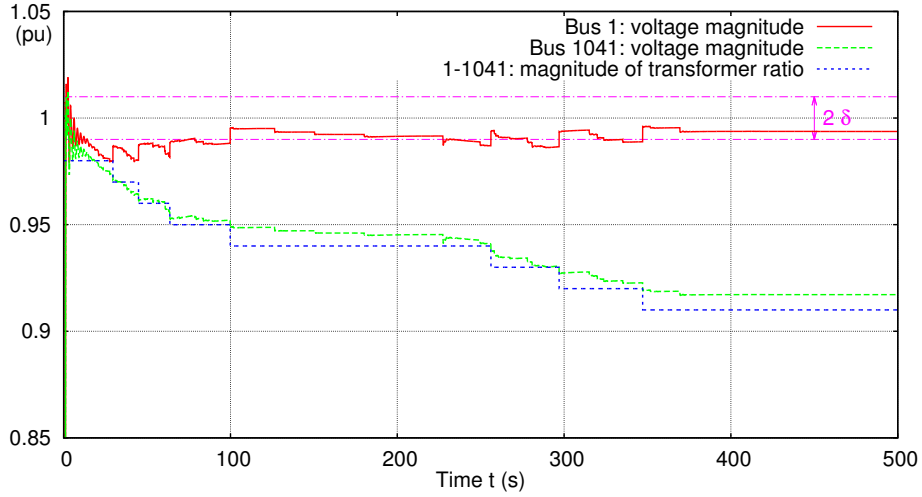


Figure 9: Scenario 2 - Bus voltage magnitude at HV bus 1041 and MV bus 41. Transformer ratio of transformer 1 – 1041.

voltage at bus 1.

4.5. Scenario 3 - Operating point B plus 375 MW

This scenario represents a marginally unstable case, which initially appears to be stable but instability is revealed in the Central area after 700 s. Table 1 lists the buses, where warnings or alarms were raised. At several buses located in the Central area (buses 1 – 5, 42, 43 and 46), warnings/alarms were issued. Outside the Central area only at bus 22 a warning was raised, but no false alarm. The table shows that for several buses only an HV Alarm is raised, e.g. bus 1, 3, 4 and 42. At these buses no eLIVES Warning and Alarm are issued, because the respective LTCs manage to restore the controlled voltage until their lowest tap position is reached. Then the voltage at the bus is not any longer controlled. As described in Section 3.2, eLIVES is subsequently deactivated after a time delay. Figure 10 shows the voltage magnitude at bus 1, bus 1041 and the ratio of transformer 1 – 1041. The voltage at bus 1 initially improves due

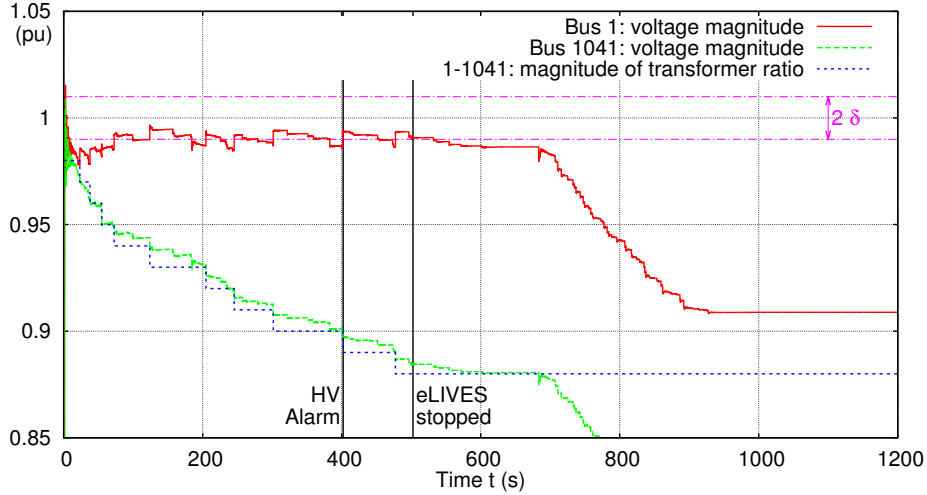


Figure 10: Scenario 3 - Voltage magnitude at HV bus 1041 and MV bus 1. Transformer ratio of transformer 1 – 1041.

to the repeated tapping action, which results in a general positive voltage trend and, hence, no eLIVES Warning is raised. However, the voltage at bus 1041 is getting significantly depressed and drops below the critical value of 0.9 pu, which is considered unacceptable. This causes the HV Alarm to be raised.

At $t = 477.3$ a last tap change occurs and the transformer hits its lower tap
 400 limit. The monitoring with eLIVES is continued for the period of $T_{max} = 25$ s
 and is stopped at $t = 502.6$ s as expected. The actual critical decrease of the
 voltage at bus 1 begins at around 680 s, where the local LTC has already hit
 its limit. Consequently, voltage instability is driven by the other LTCs, causing
 the transmission voltages to drop.

405 Also for bus 42 only an HV Alarm was triggered, but no warning or alarm
 from eLIVES was raised. Figure 11 depicts the voltage at the MV bus 42 and
 at the HV bus 4042. Again the ratio of transformer 42 – 4042 is displayed
 as well. The plot shows that the LTC repeatedly succeeds in bringing the

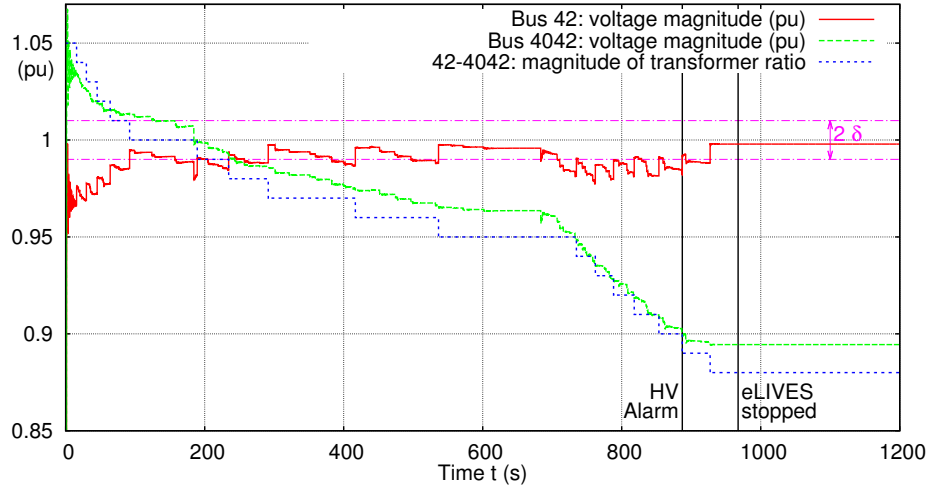


Figure 11: Scenario 3 - Voltage magnitude at HV bus 4042 and MV bus 42. Transformer ratio of transformer 42 – 4042.

voltage magnitude at the controlled bus back into the deadband. Even after
 410 700 s, where at buses 1 a declining MV voltage magnitude can be observed, the
 voltage trajectory of bus 42 shows generally a slight increase leading eventually
 to a restoration of the voltage. Since the LTC performs satisfactory and due to
 the general positive trend, eLIVES does not raise a warning and, consequently,
 no alarm, as expected. However, the multitude of tap changes causes the HV
 415 voltage magnitude to decrease and fall below 0.9 pu, which causes the triggering

of the HV Alarm.

Figure 12 displays the evolution of the voltage magnitudes at the MV bus 2 and HV bus 1042. Furthermore, the ratio of transformer 2 – 1042 is shown. It can be observed that until approximately 700 s of simulation time, the LTC

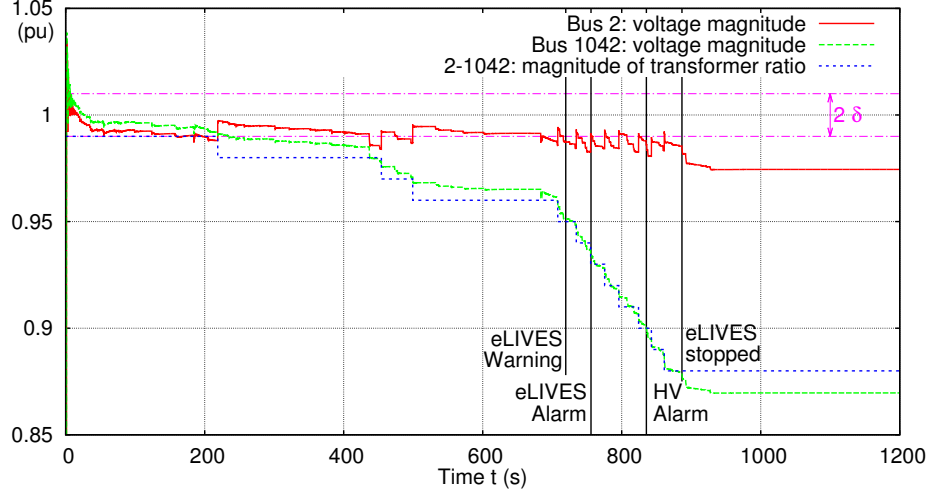


Figure 12: Scenario 3 - Voltage magnitude at HV bus 1042 and MV bus 2. Transformer ratio of transformer 2 – 1042.

420 succeeds with only few tap changes to bring the controlled voltage back into the deadband. After 700 s and despite repeated tapping, the LTC can no longer restore the voltage at bus 2. At 719.5 s, eLIVES identifies a negative trend of the voltage magnitude evolution and a warning is raised. The repeated actions of the LTC, which reduces the transformer ratio without boosting the voltage
425 magnitude on the secondary side, lead to a depression of the voltage at bus 1042, which eventually triggers the eLIVES Alarm at 755.8 s and the HV Alarm at 835.5 s. Consequently, eLIVES detects the detrimental condition 79.7 s earlier than the HV Alarm, which solely considers the HV voltage magnitude. Eventually, transformer 2 – 1042 exhausts its tap range at 861.2 s, which results
430 in deactivating eLIVES at 886.7 s.

5. Simulation results - Application to emergency control

This section illustrates a potential application of the eLIVES Alarm. The emergency control scheme is of the type described in [16], but modified to replace the central alarm decision by the local eLIVES Alarm detailed in this paper.

435 When an eLIVES Alarm is issued, the emergency control scheme is activated at the respective bus and blocks of load are shed in several steps. At activation, the voltage at the HV side is stored in V_{sh} and used as shedding criteria. Afterwards, each time when $V_{HV}(t_i)$ falls below V_{sh} a load block is shed. In this scenario, the block size was chosen to be $\Delta P = 25$ MW (plus a corresponding decrease of the

440 reactive power). After the eLIVES Alarm was raised, there is no additional delay for the initial load shedding. However, before each subsequent load shedding, a minimum time delay of 3 s is assumed.

The proposed method dynamically sets a voltage threshold used for the load shedding decision, while a standard under-voltage relay utilizes a pre-defined

445 static voltage threshold as decision criterion. In practice, it may be challenging to determine such a static threshold, which is valid in a broad variety of system operation conditions. Indeed, to avoid tripping in non-critical situations, this threshold should be chosen low enough; on the other hand, setting it too low results in greater degradation of operation and may lead to shed more. As

450 the proposed method allows identifying this threshold dynamically (at the time of the eLIVES Alarm), it can be at the heart of an adaptive system integrity protection scheme.

The effectiveness of eLIVES in combination with this load shedding scheme is presented on Scenario 1. The load curtailment succeeds in stabilizing the

455 system. For that purpose, the scheme was activated at two buses, namely bus 1 and 42. In total 225 MW load were curtailed to save the system (50 MW at bus 1 and 175 MW at bus 42). Figure 13 shows the voltage evolutions at bus 1 and 1041 as well as the ratio of transformer 1 – 1041, when the emergency scheme is applied. As shown in Section 4.3 the eLIVES Alarm at bus 1 is triggered at

460 $t = 58.2$ s (see also Table 1). The voltage threshold for load shedding V_{sh} is set

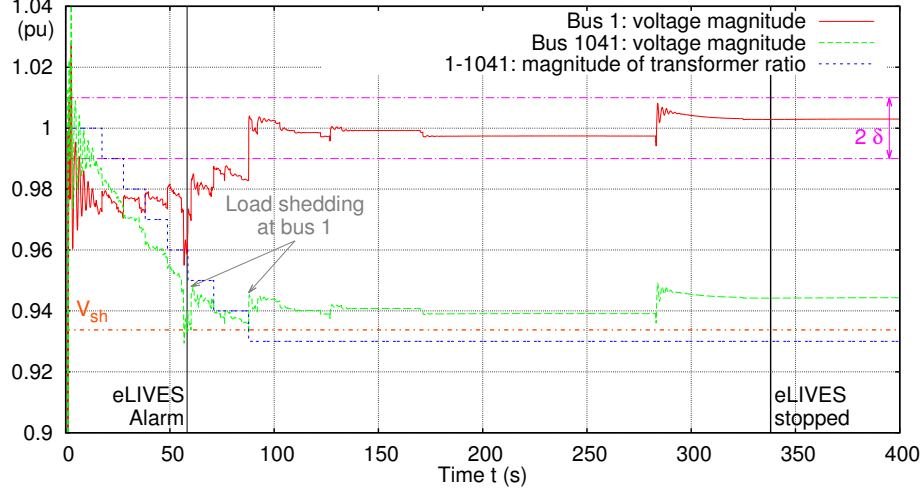


Figure 13: Scenario 1 with load shedding - Voltage magnitude at HV bus 1041 and MV bus 1. Transformer ratio of transformer 1 – 1041.

equal to the value $V_{HV}(t = 58.2)$, which is displayed as the orange dash-dotted line in Fig. 13. Shortly after at $t = 60.1$ s, the first block of load is shed, which results in a step increase of the voltage magnitude at bus 1041. Subsequently, the voltage V_{HV} drops one more time below V_{sh} resulting in load shedding at time $t = 87.8$ s (see Fig. 13). Finally, V_{HV} remains above V_{sh} and a new steady state is reached. It should be mentioned that the voltage magnitude at bus 1 re-enters the deadband after the second load shedding and settles at a value inside the deadband. Consequently, no reverse tapping of the LTC is observed. In this case, reverse tapping could indicate that the load shedding at the respective bus was excessive, which led to an overshoot of the MV voltage. Moreover, the monitoring with eLIVES is terminated at $t = 338.6$ s, since the distribution voltage stayed inside the deadband for longer than $T_{off} = 250$ s.

6. Simulation results - Robustness to measurement noise

In this section, the robustness of the proposed method with respect to noise on the input signal is assessed. The noise added to the signal could influence the

time when an eLIVES Warning, eLIVES Alarm or an HV Alarm is detected. Since the additional condition ($V_{HV}(t_{rec}) - V_{HV}(t_i) > 0.05$) for the eLIVES Alarm as well as the sole condition ($V_{HV}(t_i) < V_{HVAlarm}$) for the HV Alarm are expected to not be sensitive to noise, it was decided to focus on the investigation of the robustness of the eLIVES Warning. For that purpose, 1000 Monte-Carlo simulations of Scenario 1 were carried out, where noise was added to the voltage samples at bus 1. The noise signal was generated by drawing samples from a Gaussian distribution, where the mean was set to $\mu_{noise} = 0.0$ pu and the standard deviation $\sigma_{noise} = 0.005$ pu. The resulting voltage evolutions were assessed with eLIVES and the cumulative probability of the time at which the eLIVES Warning was raised is shown in Fig. 14.

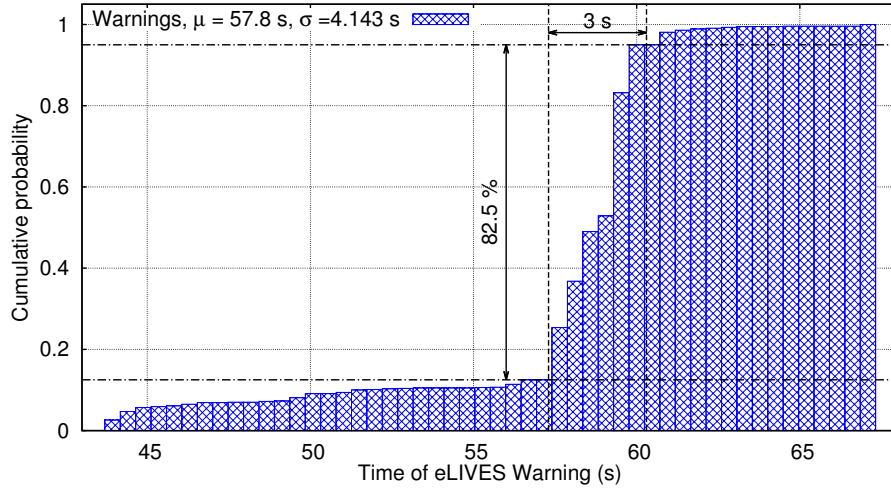


Figure 14: Scenario 1 - Cumulative probability of time of eLIVES Warning at bus 1, when noise is added to the voltage measurements.

It should be noted that in all cases an eLIVES Warning was raised in spite of the added noise and, hence, no false negative errors occurred. The mean of the time at which the eLIVES Warning was issued is 57.8 s, which is fairly close to the value obtained in the absence of noise (58.2 s see Table 1). Finally, it should be emphasized that 82.5 % of the obtained warning times are in a narrow 3 s interval between 57.3 s and 60.3 s.

7. Conclusion

In this paper the eLIVES method was proposed, which allows a local, early
495 and dependable identification of long-term voltage instability.

In order to identify a developing instability, the method monitors the evolution of the LTC controlled voltage using a linear regression model. The model is fit to the whole set of measurements with a recursive least squares approach. This allows considering the voltage evolution over the entire time period after
500 the deadband was left, but without the need to store a long sequence of values. Finally, the slope is monitored and additional safeguard rules are checked to identify if a voltage emergency situation is entered.

The proposed method was tested on the IEEE Nordic Test System. The results from three scenarios were presented and discussed. They show that
505 eLIVES can identify emergency situations reliably and early. It was shown that the eLIVES Warning accurately detects when the controlled voltage exposes a negative trend. Subsequently, when the voltage on the primary side of the LTC transformer has dropped by more than a pre-defined value, the eLIVES Alarm is issued, which correctly indicates a voltage emergency situation. Additionally,
510 an HV Alarm acts as a back-up. The proposed method did neither raise any false alarms in the stable case, nor false alarms at non-critical buses in the unstable cases. Finally, a successful application to load shedding was reported.

Among the future investigations, it is planned:

- to assess the capability of eLIVES to control the successive corrective
515 actions (as a substitute to monitoring a transmission voltage threshold);
- to embed the eLIVES method into an agent-based approach with limited communication between agents. This could result in an earlier identification of a voltage emergency situation, e.g. solely based on eLIVES Warnings.
- 520 • to investigate if a higher measurement sample rate and a filtering of the samples improves the performance of eLIVES in presence of noise.

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